## HELICAL RFPs: THEORY AND EXPERIMENT

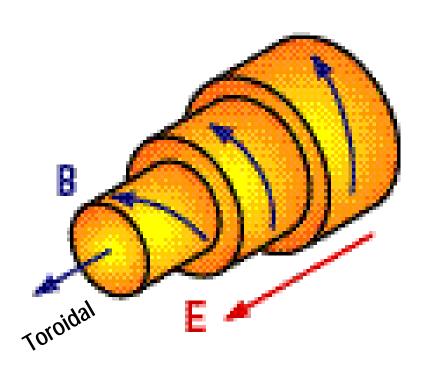
by M. J. Schaffer

**General Atomics** 

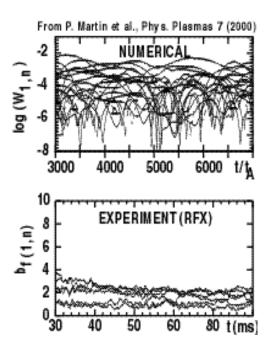
Presented at the INNOVATIVE CONFINEMENT CONCEPTS Workshop Berkeley, CA, 2000 February 22–24



# The Reversed Field Pinch Has Large Magnetic Shear Generated by Large Internal Poloidal Current



The poloidal current required for reversed B cannot be driven by a toroidal electric field alone.



Poloidal current is driven by multiple nonlinearly coupled resistive MHD modes. The result is a stochastic magnetic field across most of the RFP cross section.

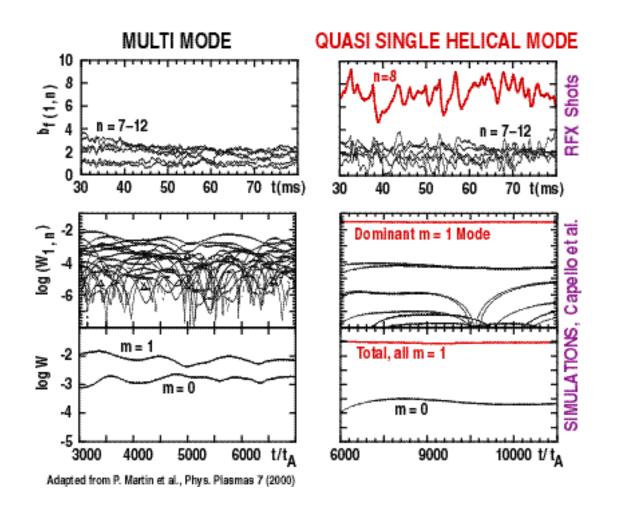


### **THESIS**

- RFP confinement is limited by the magnetic fluctuations and stochasticity that sustain the reversed field.
  - ➤ Want to replace self-driven poloidal current by something more benign.
- Quasi single helical mode (QSH) states in RFP experiments and numerical simulations yield reduced stochasticity and improved confinement.
  - ➤ QSH is difficult to produce and control in a circular-section axisymmetric torus.
- The validity of the Helical RFP is already established. Confinement is improved.
- "Helical-D" generates a robust reversed magnetic field by geometry.
  - ➤ Has <u>deliberate</u> helical shaping and a <u>deliberate</u> helical equilibrium.
  - ➤ Greatly reduces need for poloidal current, but enough to eliminate instabilities?
  - > Helical-D geometry complicates engineering, like stellarator's.
- A deliberate helical equilibrium between the extremes of circular and helical–D
  might offer the best of both worlds and should be explored.



## RFP Experiments Sometimes Enter a Quasi Single Helical (QSH) State



- One m = 1 helical mode
   dominates over all other m = 1
   and m = 0 (sausage) modes.
  - Sometimes the QSH state lasts for a long time, sometimes it exists only briefly.
- Plasma confinement improves during QSH phase.
- QSH mode states have been observed in:

TPE-1RM20

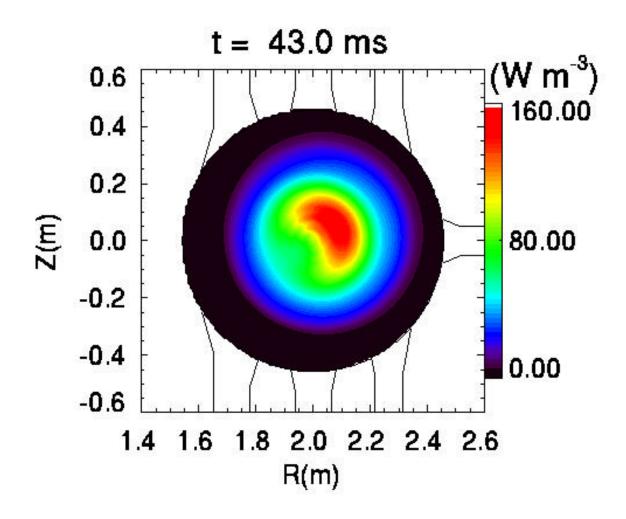
Extrap T1

**RFX** 

## Helical Structures Are Experimentally Observed in RFX

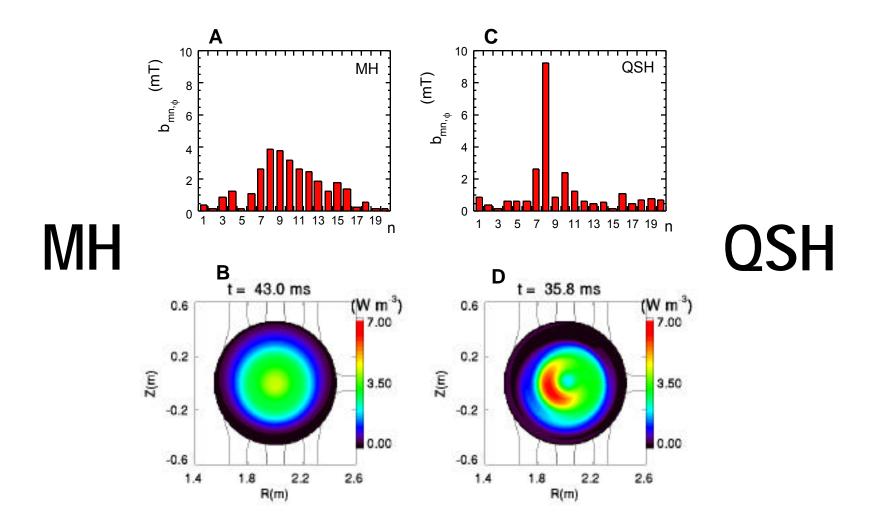
Tomographic reconstruction of Soft X–ray data.

High emission helix coincides with the helical magnetic island reconstructed from magnetic data.





# The SXR Helical Structure in RFX is Associated with Quasi Single Helical (QSH) Magnetic Mode, but Not with Multiple Helical (MH) Modes

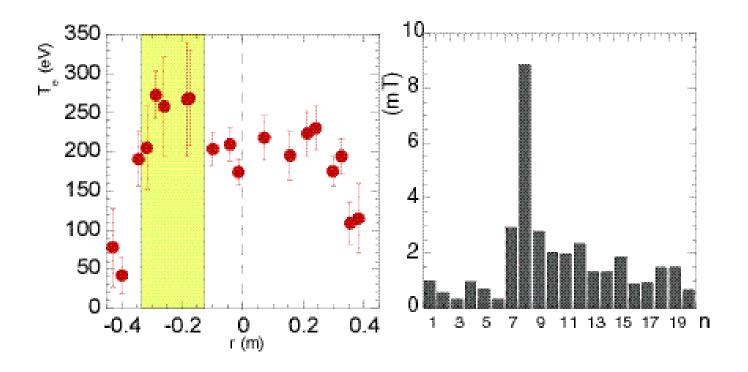




## An Artist's Conception of the Helical Structure



## Plasma Temperature Increases Inside Quasi Single Helical Mode Island

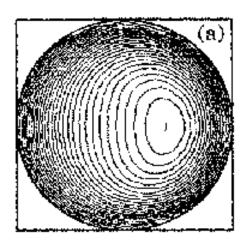


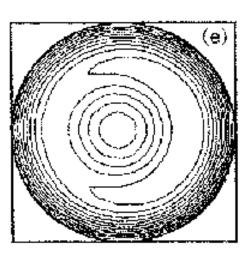
- Thomson scattering data show higher T<sub>e</sub> inside the magnetic island during quasi single helical mode event.
- T<sub>i</sub> increases, too (not shown).



## Single Helical Mode Equilibria Were Generated Numerically for a Viscous Resistive Plasma

- Numerical 3D simulations of viscous, resistive plasmas have yielded quasi single helical mode (QSH) equilibria.
  - Cappello & Paccagnella; Finn, Nebel and Bathke; Cappello & Biscamp; Cappello et al.
- In these studies, viscosity must dominate to make QSH state appear (Pr =  $\tau_{resist}/\tau_{visc} >> 1$ ).
  - Bifurcated system.
    - Pr < 1 yields multihelical mode solutions.</li>
    - Pr >> 1 yields QSH solutions. Required Pr increases with Lundquist number S.
- Viscosity of experiments is unknown.





Finn, Nebel & Bathke, Phys. Fluids B <u>4</u> (1992) 1262.



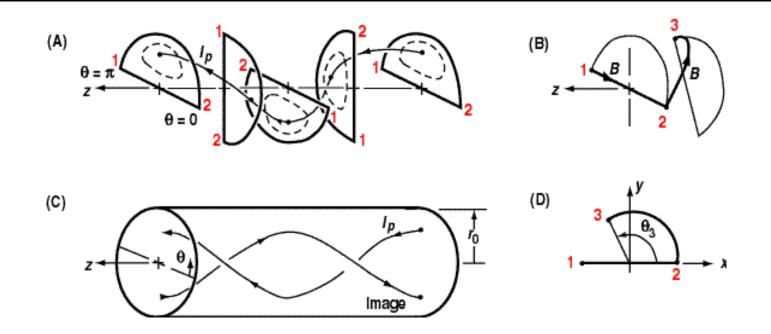
## THE HELICAL-D PINCH\*

# A Helical RFP with Large Reversal and Small Poloidal Current

\*M. SCHAFFER, COMMENTS PLASMA PHYS. CONTROLLED FUSION 18 (1999) 349.



# Helical-D Transform is a Geometrical Effect — a Combination of the Helical Axis and D-Shaped Cross Section



- The magnetic field from a helical current filament (representing plasma) in a helically twisted, D-shaped ideal shell has a strong reverse pitch near the boundary.
- B points straight across the D "flat" (from point 1 to 2 in the figures).
  - Shell image currents are equivalent to a helically twisted pair of currents (Fig. C).
- ullet B at the circular wall surface (from 2 to 3 in Fig. B), is  $\bot$  to the helically ignorable coordinate.
  - The line steps back in z, oppositely to the direction of the filament's current.



## Helical-D Transform is Large and Broadly Distributed

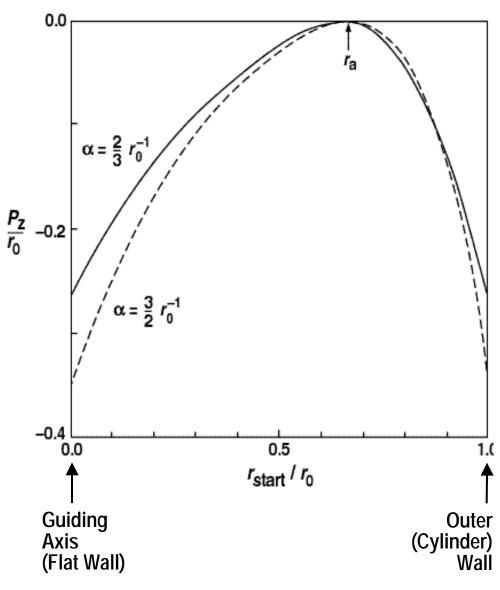
- Here the plasma is modeled as a sheet of current in the helical direction at  $r = r_a$  in an ideal Helical–D shell of pitch  $\alpha$ .
  - No poloidal currents in model.
- The plot shows the pitch of numerically traced magnetic lines.

Linear Pitch = 
$$P_7 \equiv$$

Advance in z

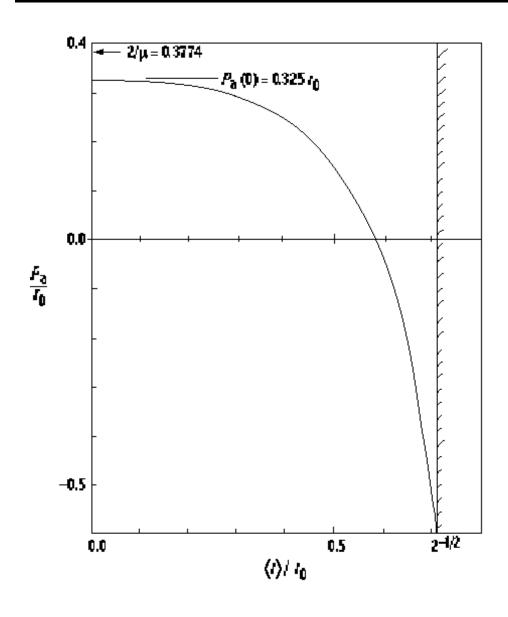
radians around magnetic axis

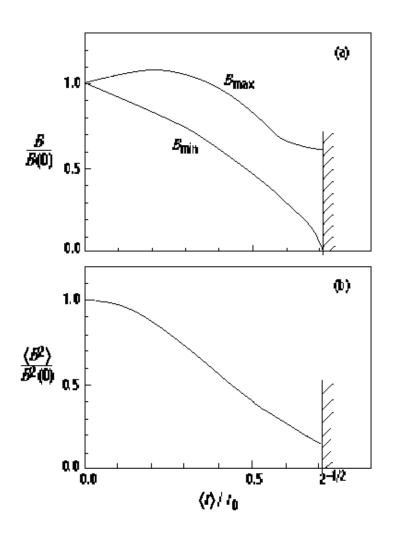
 The pitch and shear are well distributed throughout the volume, not localized at separatrix.





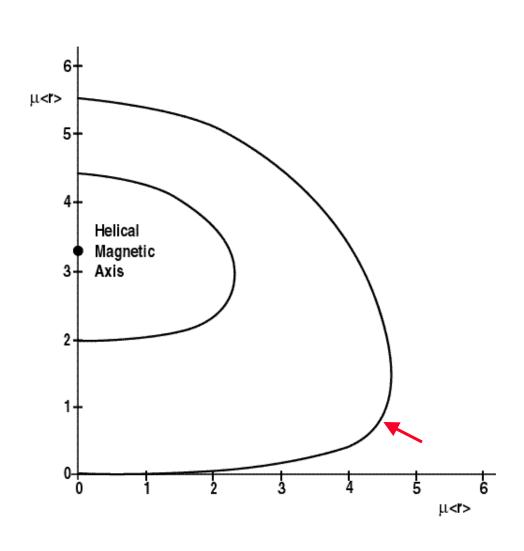
# Taylor–Relaxed in Semi Circular Helical Shell Has Large Reversal and Shear, but Too Much Poloidal Current and |B| Variation on a Magnetic Surface

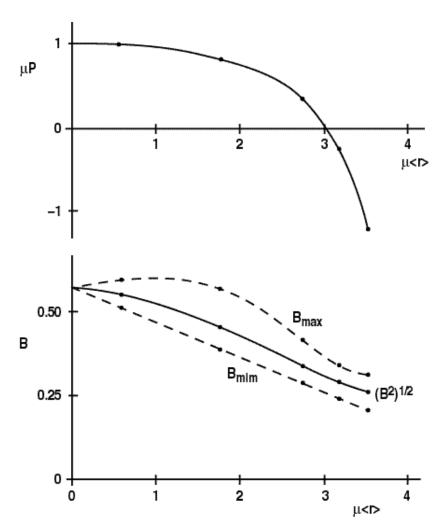






# If the D-corners are Rounded, the Taylor-Relaxed Helical-D Equilibrium Still Has Large Transform, and |B| Variation is Reduced







### Some Directions for Helical RFP Research

- The goal of helical RFP research is to make an <u>Ohmically</u> sustained reversed–PITCH helical pinch that needs little or no poloidal current.
  - Then the magnetic fluctuations should be low and confinement good.
- A cross sectional shape that is roughly circular in the plane perpendicular to the helical magnetic axis might minimize |B| variation on a magnetic surface (minimize neoclassical effects).
  - Also easier to construct.
- A helix with a somewhat smaller helical magnetic axis radius (relative to outer surface radius) is also easier to construct.
- Need to do numerical tradeoff of various physics and engineering considerations.
- Helical RFP feasibility and optimization can be studied numerically with existing codes.
  - 3-D resistive MHD codes.
  - 3-D stellarator equilibrium code, such as VMEC.



#### CONCLUSIONS

- Numerical simulations yield 2–D Single Helical (SH) and 3–D Quasi Single Helical mode (QSH) states.
- QSH states have appeared in RFP experiments.
  - >Stochasticity is reduced. Confinement is increased.
- QSH is difficult to make and control in a circular-section axisymmetric torus.
- The validity of the Helical RFP is already established.
  - Confinement is improved.
- "Helical-D" geometry generates a robust reversed magnetic field by axial transform.
  - ➤ Need for poloidal current is greatly reduced.
- A deliberate helical equilibrium between the extremes of circular and helical–D might offer the best of both worlds and should be explored.

